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THE METALLICITY OF PRE-GALACTIC GLOBULAR CLUSTERS: OBSERVATIONAL CONSEQUENCES OF THE FIRST STARS

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ABSTRACT

We explore a scenario where metal-poor globular clusters (GCs) are enriched by the first supernovae in the Universe. If the first stars in a 10^7 $M_\odot$ dark halo were very massive (> 180 $M_\odot$), then a pair instability supernova from a single massive star can produce sufficient iron to enrich $10^6\,M_\odot$ of pristine, primordial gas to [Fe/H] ~ -2. In such a scenario, where a single massive star acts as a seed for halo GCs, the accurate abundance analysis of GC stars would allow a direct measurement of the Population III initial mass. Using the latest theoretical yields for zero metallicity stars in the mass range $140-260$ $M_\odot$, we find that the metals expelled from a ~ 230 $M_\odot$ star are consistent with [Si/Fe] and [Ca/Fe] observed in GC stars. However, no single star in this mass range can simultaneously explain all halo GC heavy-element abundance ratios, such as [V/Fe], [Ti/Fe] and [Ni/Fe]. These require a combination masses for the Population III stellar progenitors. The various observational consequences of this scenario are discussed.

Subject headings: stars: Population III—globular clusters: formation —globular clusters: general—early universe

1. INTRODUCTION

Globular clusters (GCs) are dense, bound systems of typically $10^4 - 10^6$ $M_\odot$ stars. They differ from galaxies in that their stellar populations are coeval and have extremely uniform [Fe/H]. Measurements of [Fe/H] (taken to trace overall metallicity) show that there appear to be at least two distinct sub-populations of GCs in the Galaxy. One represents a spherically distributed halo population, with mean [Fe/H] ~ -1.5, the other is spatially flattened, with a higher mean metallicity ([Fe/H] ~ -0.5) (Zinn 1985). This division is also seen in the kinematics of the two sub-populations, the halo GCs are largely a pressure-supported system, whereas the metal-rich GCs show signs of net rotation leading them to be associated with the thick disk (Zinn 1985) or the bulge (Frenk & White 1982). There now exists substantial evidence for multiple populations of GCs in external galaxies (see Ashman & Zepf 1998 and references therein), which exhibit similar metallicity distributions to those of the Milky Way.

The existence of correlations between the mean metallicity of the metal-rich GCs with the mass of their parent galaxies (e.g., Forbes & Forte 2001), suggests that they are somehow connected to the formation of the spheroid. However, their halo counterparts show only weak evidence for such correlations with their parent galaxy properties, suggesting different formation sites and/or formation processes for these objects.

In attempting to explain the origin of these GCs we must address the following questions: *(i)* why do GCs have a characteristic mass scale? *(ii)* why do they coalesce so rapidly after the big bang (a recent mean age for Galactic GCs is 12.9 ± 2.9 Gyr (Carretta et al. 2000), whilst WMAP puts the age of the Universe at 13.7 ± 0.2 Gyr (Spergel et al. 2003))? *(iii)* why are their metallicities so homogeneous? *(iv)* why do they have a characteristic mean metallicity of [Fe/H] $\sim$ –1.5 with a lower bound of [Fe/H] $\sim$ –2.5?

Here we consider the view that at least some halo GCs are 'pre-galactic' in origin (i.e., form before the bulk of the galaxy stars). The idea of pre-galactic GCs is not new, and was first discussed in any detail by Peebles & Dicke (1968). Peebles (1984) suggested that the hierarchical clustering scenario yields two characteristic scales; one of which might be identified with GCs which form within collapsed dark matter (DM) halos prior to galaxy formation. Previous studies which have considered cooling processes in a cold dark matter (CDM) universe, suggest that the first stars may form within a collapsed DM halos of $10^5 \sim 10^7$ $M_\odot$ (e.g., Tegmark et al. 1997; Yoshida et al. 2003). Therefore, a pre-galactic GC formation scenario can explain the above questions *(i)* and *(ii)* naturally. In addition, any nucleosynthetic products, the result of star formation occurring in such low-mass DM halos, may be expected to have a short mixing timescale leading to a homogeneous chemical composition (*(iii)*). However, question *(iv)* is crucial. If GCs are the first objects, they have to form from pristine (i.e., zero metallicity) gas, and are therefore expected to have low metallicities (Peebles 1984).

In this *Letter*, we investigate a scenario to address question *(iv)* in particular. We consider that a single very massive ($> 150\,M_\odot$) 'first star', with a consequently short lifetime ($\sim 10^6$ years), forms in a virialised halo at very high redshift (e.g., Abel, Bryan & Norman 2002). The star explodes as a supernova and enriches the pristine gas in the halo, resulting in the formation of a GC with a characteristic abundance pattern. Recent models of the metal production and ejection of stars with primordial compositions (Hegar & Woosley 2002, hereafter HW02) show that

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in a star of above $\sim 150\,M_\odot$, the amount of iron produced and ejected as a supernova jumps to several solar masses. This is adequate to comfortably enrich $10^6\,M_\odot$ of gas (in a $10^7\,M_\odot$ DM halo) to the abundances seen in Milky Way halo GCs (offering an explanation for *(iv)*). The metals ejected from the death throws of a single giant Pop. III star will act as an efficient coolant (Omukai 2000) significantly increasing the local cooling rate. This may lead to a rapid burst of star formation within enriched gas with a normal initial mass function (IMF). Further star formation is arrested when type II supernovae (SNeII) within the GC expel the remaining gas, enriching and possibly reionising the interstellar medium (ISM) (e.g., Yoshii & Arimoto 1987, Massimo 2002).

Before investigating this scenario in more detail, we note that it is quite likely that GCs form in a variety of different processes. Indeed, there are many scenarios which address the above questions, and generally favour the idea that GC formation is a purely baryonic process (e.g. Fall & Rees 1977; Fall & Rees 1985; Caputo & Castellani 1984; Kang et al. 1990; Bromm & Clarke 2002; Kravtzov & Gnedin 2003). This study does not exclude any of the above ideas, but we argue that on the basis of current theoretical understanding, and observational evidence, a cosmological origin for halo GCs cannot be ruled out. We consider that our scenario is a possible solution to the problems alluded to previously, and here we test it severely. Moreover, our scenario does not impinge upon the second peak of the GC metallicity distribution. Young clusters can be formed when gas clouds are shocked, for instance during major mergers that result in the final host. As Beasley et al. (2002) argued using semi-analytic techniques, separate formation epochs and/or mechanisms may be required to reproduce the observations.

2. A SINGLE VERY MASSIVE STAR

By definition, the first star should have primordial abundance, i.e., zero metallicity. Nucleosynthesis calculations for zero metallicity stars are still controversial, nevertheless, due to the extensive work of several groups (e.g., HW02; Limongi & Chieffi 2002; Umeda & Nomoto 2002, hereafter UN02), a consensus is rapidly evolving. According to HW02, the enriched ejecta are sensitive to the progenitor star's main sequence mass; non-rotating stars over $260\,M_\odot$ do not eject any metals because they become black holes which consume all subsequent ejecta (e.g., Fryer, Woosley & Heger 2001). Between approximately 140 and $260\,M_\odot$ lies the domain of pair instability SNe (PISNe). These stars are completely disrupted by nuclear-powered explosions. Below this mass range it is again likely that black holes are the main product, and little heavy elements are ejected (Fryer 1999; Woosley & Weaver 1995). As PISNe do not result in a black hole, their explosion mechanism is well understood, compared to core-collapse SNe (CCSNe), and their ejection products calculable. Moreover, unlike CCSNe, PISNe are not affected by the "mass cut", which is the mass coordinate that separates the ejecta from the compact remnant, i.e., the mass inside of the mass cut has never been ejected. a "mass cut", which is the mass coordinate at which the explosion energy is deposited, i.e., the mass inside of the mass cut has never been ejected (Limongi & Chieffi 2003). This mass cut, which is a free parameter in CCSNe models and to some degree governs the iron yield, is not needed in PISNe models.

We consider stars within the mass range of 140 to $260\,M_\odot$ and adopt the yields for those stars calculated by HW02. Fig. 1 shows the expected iron abundance when a single massive PISNe enriches a given mass of pristine gas. The horizontal solid line shows the observed mean metallicity for Galactic halo GCs ([Fe/H]$= -1.62$), the dotted lines show the dispersion on this value ($\sigma = 0.32$; calculated from the February 2003 version of the Harris (1996) catalogue). The lines for each star with indicated masses are calculated by $[\mathrm{Fe/H}] = \log(M_{\mathrm{ej,Fe}}(m_s)/(0.76M_{\mathrm{g}})) - \log(Z_{\mathrm{Fe},\odot}/Z_{\mathrm{H},\odot})$. $M_{\mathrm{ej,Fe}}(m_s)$, M_{g}, $Z_{\mathrm{Fe},\odot}$, and $Z_{\mathrm{H},\odot}$ are the iron yield for a $m_s\,M_\odot$ star, the mass of pristine gas, the solar metallicities of iron and hydrogen respectively. The value of 0.76 is the primordial hydrogen abundance. We employ the solar abundance shown in Anders and Grevesse (1989; see Woosley & Weaver 1995), and assume that the ejected metals are homogeneously distributed, i.e., the one zone model.

The iron yields of HW02 increase with increasing stellar mass. For a typical GC of $10^5\,M_\odot$, forming stars at 100% efficency within a $10^6\,M_\odot$ halo, the mass of a single Pop III star must be above $180\,M_\odot$. Since the star formation efficiency is more likely to be $\sim 10\%$, the mass of the first star must be $> 220\,M_\odot$ embedded in a $10^7\,M_\odot$ halo. This mass range is consistent with the mass of the first stars predicted by numerical simulations ($\sim 200\,M_\odot$; e.g., Abel, Bryan, & Norman 2000). Thus, Fig. 1 demonstrates that the explosion of a *single* massive star is capable of enriching gas to the metallicity levels seen in halo GCs. This may explain the characteristic range in the metallicities of halo GCs, as the individual DM halos have a characteristic size, and the stars a limited mass range. Note that a mass-metallicity relation for GCs is not necessarily expected in this model (e.g. Murray & Lin 1992), since there may well be dependency between M_{g} and stellar mass.

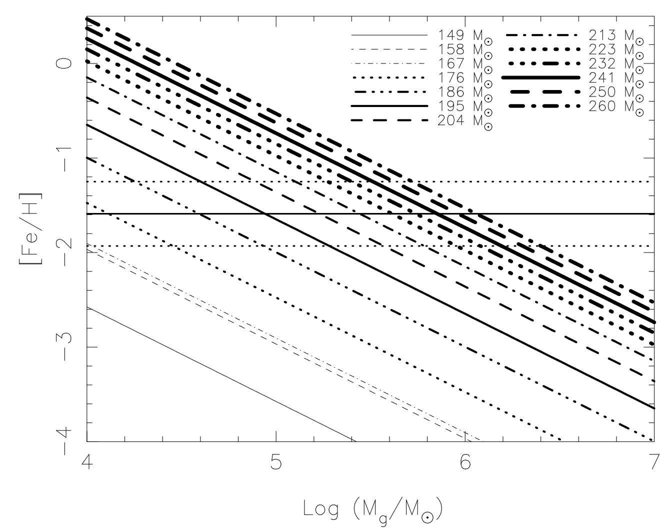

FIG. 1.— The iron abundance produced when a single massive PISN of a given mass enriches the amount of pristine gas shown on the ordinate. The horizontal line shows the observed mean metallicity ([Fe/H]$=-1.62$) for halo GCs. Dotted lines show the dispersion ($\sigma = 0.32$; see text).

Here we consider the case that the first star is a sin-

gle very massive star, and induces a PISN. However, stars with main sequence masses between ~ 8 and ~ 40 $M_\odot$ can also produce heavy elements through CCSNe. Although, as mentioned previously, the iron yields of CCSNe are affected by poorly constrained parameters such as the mass-cut, the expected highest possible iron yields from CCSNe (30 $M_\odot$ star in UN02) are ~ 0.2 $M_\odot$. To enrich the halo pristine gas to the same level as a 232 $M_\odot$ star, which produces 19.4 $M_\odot$ iron, at least ~ 95 CCSNe are required. Thus, although multiple CCSNe are another possible means of adequate iron enrichment, a total of 2850 $M_\odot$ of gas must be converted to stars effectively simultaneously. Therefore, although not a unique solution, a single PISN is a more efficient (and plausible) enrichment mechanism.

3. ELEMENTAL ABUNDANCES

One consequence of our scenario is that the observed abundances for different metals within a single GC should be due to enrichment from a *single* star. By comparing the observed abundances with the predicted yields of HW02 we may read off the mass of the first star responsible for each GC. Fig. 2 shows the various abundance ratios of PISN yields of HW02 as a function of progenitor stellar mass. The dotted lines are the observed range of the abundance ratios for stars in several Galactic GCs. The observed abundance ratios come from high resolution spectroscopic data of RGB stars, in which the lighter elements, such as O, Na, Ma, and Al, are possibly affected by stellar evolution such as dredge up. Thus, we here focus on relatively heavy elements, i.e., heavier than Si, which should be unaffected by such evolutionary processes. The panels of [Si/Fe] and [Ca/Fe] show that a star of mass between 220 and 240 $M_\odot$ is in remarkably good agreement with the observational data. Such stellar masses are consistent with the range discussed previously. Thus, a star with mass around 230 $M_\odot$ is a strong candidate for the first star in our GC formation scenario.

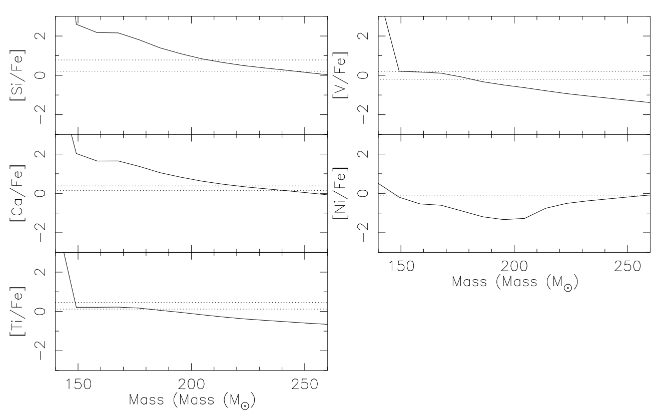

FIG. 2.— The abundance ratios from PISN yields as a function of the main sequence mass of the progenitor star. The dotted line shows the range, i.e., maximum and minimum, of the abundance ratios in observed GCs (NGC 6287, NGC 6293, NGC 6541: Lee & Carney 2002; M4: Ivans et al. 1999; NGC 7006: Kraft et al. 1998; M15: Sneden et al. 1997; M13 Kraft et al. 1997).

However, we find that the yields for this mass cannot reproduce all the abundance ratios observed. For example, the other panels of Fig. 2 demonstrate that [Ti/Fe], [V/Fe], and [Ni/Fe] for a 230 $M_\odot$ star is significantly below the observed range. The observed range of [Ti/Fe] and [V/Fe] requires a star of < 180 $M_\odot$, whilst [Ni/Fe] requires a star with less than 150 $M_\odot$, or greater than 250 $M_\odot$. This is clearly a problem for the model; the theoretical yields and observations could be reconciled by postulating enrichment from a small number of stars rather than a single star, e.g., the combination of a 230 $M_\odot$ stars, and several < 150 $M_\odot$ stars. However, the most serious problem of PISN enrichment for GCs is the absence of any elements above the iron group due to a lack of any s- and r-process (HW02). In the stars of the GCs in Fig. 2, elements such as Ba, La, and Eu are present in significant quantities. Additional physics such as rotation of the massive star, or subsequent pollution of the immediate environment could provide solutions to this problem. Alternatively, there may some additional contribution from normal CCSNe, although this makes the scenario less appealing.

Since accurate stellar abundances are crucial to this issue, and the sample of GCs with such measurements is small, we strongly encourage high resolution spectroscopic measurements of individual stars in a larger sample of GCs. In addition, since many species may be effected by the mixing of nuclear products in cluster giants (e.g. Kraft 1994), such analyses should be applied to main-sequence stars providing reliable abundance ratios for lighter elements such as [O/Fe] and [Mg/Fe].

As a result, although the proposed scenario can explain several observational properties of GCs, there some are serious problems. The current generation of population III yields favour the formation of multiple stars (which should be more than 8 $M_\odot$) over a single massive star, with the inclusion of a source of neutron-capture elements.

4. OBSERVATIONAL CONSEQUENCES

There are several interesting observational consequences of our proposed scenario. If the abundance ratios predicted by the PISN yields can be reconciled with the observations, and they are the result of a single massive first star, then the mass of that star could be derived. With sufficiently detailed abundance ratio observations of GCs, the mass of the precursor Pop. III object could be extracted, which, combined with the mass of the GC would allow the star formation efficiency to be calculated.

If all Pop. III stars were very massive, then none will survive to the present day. Very low metallicity stars, such as that recently observed in the halo of our galaxy (Christlieb et al. 2002) with [Fe/H] ~ -5 could in fact be *younger* than the halo GC population. Such stars may simply have formed out of gas enriched by some secondary 'normal' SNe II in the GCs, and such low abundances could just be the result of dilution with pristine, or very metal-poor gas (for an alternative view, see Limongi et al. 2003).

The GCs produced in our scenario form out of enriched gas such that they have a normal IMF. They produce normal numbers of SNeII [3] which serve to end further star

[3]The number of SNe II (from stars with the mass of $> 8M_\odot$) expected from a Salpeter IMF (mass range between 0.1 and 60 $M_\odot$) is ~ 730. The total energy of SNe II (730×10^{51} erg) is slightly larger than the energy of 230 $M_\odot$ PISN (60×10^{51} erg). Subsequent to star formation, which consumes the gas, the remaining gas density would be low. Therefore, we expect that these SNeII would have more power to blow out

formation by expelling the remaining gas, a mechanism which naturally produces a population of stars with a very uniform age. The gas expelled by these SNe would have abundances typical of a more normal stellar population, rather than those for Pop. III stars. Thus field stars, the diffuse ISM and the Lyman$-\alpha$ forest could consist of gas enriched by normal SNeII products.

Is is also interesting to speculate whether or not these GCs would be visible using the next generation telescopes, such as the *James Webb Space Telescope* (Carlberg 2002). If detectable, then the angular correlation function would make it possible to distinguish between GCs in their own halos or GCs associated with galaxies as larger halos have a higher correlation amplitude. Although many of our halo GCs will have subsequently fallen into larger halos (Monaco *et al.* 2002) some will have survived as free floating GCs to the present day (e.g., West 1993).

5. DISCUSSION AND CONCLUSIONS

We have demonstrated that there does indeed appear to be enough iron production within such a single massive star to enrich $10^6\,\mathrm{M}_\odot$ of gas to the levels required to reproduce 'halo' GC iron abundances. Also, abundance ratios such as [Si/Fe] and [Ca/Fe] predicted from the yields of stars with around $230\,\mathrm{M}_\odot$ are consistent with those observed in Galactic GCs. However a deficit other elements (e.g. Ti, V, N) and complete absence of elements above the iron group results in inconsistencies with the current observational data. This problem could be circumvented either by postulating an initial giant binary system, fragments of several stars (Nakamura & Umemura 2001), or missing physics in the nucleosynthesis models of giant stars, such as rotation. Further investigation of this point requires both more sophisticated numerical simulations, and more detailed models of high mass, zero metallicity stars. Irrespective of these difficulties, we argue that the detailed abundance analysis of main-sequence stars in GCs provides important clues to the nature of Population III objects.

We have assumed that the pristine gas in the collapsed halo was not completely blown away by the first PISN. For $230\,\mathrm{M}_\odot$ the energy is $\sim 60 \times 10^{51}$ ergs (HW02). If the gas fraction in the collapsed halo is the same as the cosmic mean ($\Omega_b/\Omega_0 = 0.04/0.27$: Spergel et al. 2003), and both the DM halo and the gas follow the density profile suggested by Navarro, Frenk, & White (1997), then for a formation redshift, $z = 15$ and a concentration parameter, $c = 4$, the binding energy for a gas mass of $10^6\,\mathrm{M}_\odot$ is predicted to be $\sim 3 \times 10^{51}$ ergs. As this is well below the hypernova energy, we should expect the gas to be blown out of the halo, preventing the induction of a second generation of star formation that makes the GC. However, according to high resolution 1-d simulations of a single SN remnant by Thornton et al. (1998), 90 % of an initial SN energy is lost to radiative cooling in its early expansion phase. In this case the SN energy for $230\,\mathrm{M}_\odot$ becomes comparable to the binding energy. Moreover, the ambient gas density increases with redshift, and radiative cooling is expected to be even more efficient in such high density gas. High resolution numerical simulations of a single SN in a collapsed halo at high redshift would be extremely useful to test this idea (e.g., Mori, Ferrara, & Madau 2002; Bromm, Yoshida, & Hernquist 2003 [4]). Such simulations would enable us to investigate how smoothly metals are mixed with halo gas, since our picture assumes an instantaneous, well-mixed solution.

Finally, we discuss perhaps the most important hurdle for any cosmological GC scenario. Moore (1996) pointed out that the prominent tidal tails observed for some GCs, such as M2 (Cudworth & Hanson 1993) suggests that such GCs do not possess DM halos. He supported this argument with a simulation of a GC orbiting in a static potential. The analytic argument presented by Moore (1996) derives the tidal radius for M2 with and without DM, with the former being closer to the observed truncation radius of 60pc. However, this argument does not discuss the formation time of the GC or the characteristic radius of the GC DM halo. The characteristic radius of a $10^7\,\mathrm{M}_\odot$ halo forming today is several kpc, much larger than the tidal radius derived for M2. GCs form at high redshift, therefore their characteristic radii are much smaller and they could potentially have retained much of their halos. This argument misses the major drawback of this simple analytic approach – the environment of the GC is not expected to remain smooth during the formation epoch of a large host halo, which is built up by a succession of mergers. Even today, at the radius of $8-10$ kpc, the halo is not symmetric as the potential of the disk is not negligible, supplying periodic impulses to any orbiting object. We believe that the above estimate for the tidal radius is too simplified. Numerical simulations similar to those of Moore (1996), but including the active evolution of the halo potential and/or the disk potential would be an extremely useful test for the existence of DM in GCs.

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the remaining gas from the system than a single PISN.

[4] Mori et al. (2002) focus on the effect of multiple SNe on a slightly larger system 10^8 h^{-1} $\mathrm{M}_\odot$. Bromm et al. (2003) consider a single PISN effect on a system of a similar size to that which we consider here. However, their poor DM particle resolution is reason for concern, which is likely to underestimate the gravitational potential of DM halo.

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